

# **TYNDALL AFB PHOTOVOLTAIC POWERED RESIDENCE**

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**AIR FORCE ENGINEERING AND SERVICES CENTER  
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## PREFACE

The TriSolar Corporation, 10 DeAngelo Drive, Bedford, MA 01730, under Contract Number FO8635-81-CO361, served as the prime contractor for the installation and operation of the 2-kilowatt photovoltaic (PV) system designed and developed by the Air Force Engineering and Services Center (AFESC), Tyndall Air Force Base, Florida 32403-6001. This effort was sponsored by the U.S. Department of Energy (USDOE) under the auspices of the Federal Photovoltaic Utilization Program (FPUP).


The Facility Systems and Analysis Branch analyzed system performance and prepared the technical report. This report summarizes work done between June 1983 and August 1984. HQ AFESC/RDCS project manager was Mr. Thomas C. Hardy. The USDOE agent was Mr. Joseph F. Wise, HQ ASD/POOC, Wright Patterson Air Force Base, OH 45433.

This report has been reviewed by the Public Affairs (PA) Officer and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nationals.


This report has been reviewed and is approved for publication.




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## SECTION I

### INTRODUCTION

#### A. OBJECTIVE

The objective of this program was to install workable photovoltaic prototypes in a residence where real-life performance data could be acquired. A secondary motive was to familiarize the public with the potential of photovoltaic power systems.

#### B. BACKGROUND

The 1973 oil embargo mandated an alternate energy technology in the United States. Attention was focused on active solar systems, which mechanically capture the sun's heat, and photovoltaic (PV) solar cells, which convert sunlight directly to electricity. The United States Department of Energy (USDOE) was responsible for the Federal Photovoltaic Utilization Program (FPUP) and the management of future photovoltaic energy commercialization programs for the accelerated procurement and installation of PV electric systems for the production of electricity at federal facilities. The overall thrust of the program sought to quickly reduce government fossil-fuel costs, minimize life-cycle costs, and create a performance data base for follow-on development of alternate energy technology.

The Air Force Engineering and Services Center's (AFESC) Research and Development Laboratory designed and developed the photovoltaic system for Tyndall AFB, Florida. As a part of its effort, USDOE funded the project through FPUP, Cycle III, to improve the technology. At its inception, the program had one of the most promising near-term applications for photovoltaics: reducing the cost through mass production, recognizing that the greatest influence on the feasibility of broader application is the manufacturing cost of the photovoltaic cells. Before this program, the principal application of photovoltaics had been for power generation aboard earth satellites, where cost was not typically a limiting factor.

Solar cells have come a long way since they powered early spacecraft at \$1000 a peak watt. About 8 years ago, federally sponsored research and development efforts had reduced the cost to \$10 per peak watt, raising the expectation that the residential application of PV might be feasible.

An American, Charles Fritt, developed the first solar cell in the late 1800s. These cells were composed of small selenium wafers covered by a transparent gold film. When struck by sunlight, these cells generated a continuous, constant electric current. Few people evinced interest in the cells, and work did not progress beyond the initial experimentation. In the early 1930s, the selenium solar cell was rediscovered and further refined. However, due to its high cost and extremely low efficiency (less than 1 percent of the light energy absorbed by a cell was converted to electricity), the cell's commercial development was again hindered. In 1954, researchers at the Bell Telephone Laboratories accidentally discovered that silicon, mixed with some impurities, also generated electricity when exposed to sunlight. The first solar cell designed with silicon converted 4 percent of incoming sunlight to electricity (a conversion efficiency four times greater than that of the best selenium cell). Within months, a conversion efficiency of 15 percent had been achieved. The first use of the solar cell as a commercial power source was in rural Georgia, where Bell Laboratories used it to power a telephone relay station. In most cases, PV continues to be a cost-effective method to power remote systems.



### C. PROJECT DESCRIPTION

The technical requirements for this contract effort (Contract No.F08635-81C-0361, "Tyndall AFB Photovoltaic Home," performed by TriSolar Corp.) were divided into three tasks:

1. Design of a 2-kilowatt photovoltaic utility interactive power system for the Florida area.
2. Construction and roof-load analysis of the power system on a military residence at 3140A Guardian Circle, Tyndall AFB, FL (Figure 1); electrical connection of the PV array to the existing electrical grid and power conditioning equipment.
3. Preparation of monthly reports, design reports, an O&M manual, testing and operation of the system, and submission of a final report.

The above tasks were completed as scheduled; the test results are the subject of this technical report. The house retrofit design met the technical criteria for performance, safety, and aesthetics.

This project was to supply a 2-kilowatt output photovoltaic system integrated with a 4-kilowatt direct current-to-alternating current Gemini inverter with a TriSolar Corp. direct current interface (Figure 2) with protective equipment (lightning protection, alternating current dropout relay), electrical metering, consisting of a racheting watt-hour meter, and instrumentation housed in a weathertight structure next to the residence on which the PV system was to be installed.



Figure 1. Photovoltaic Array Installed on Tyndall AFB Residence

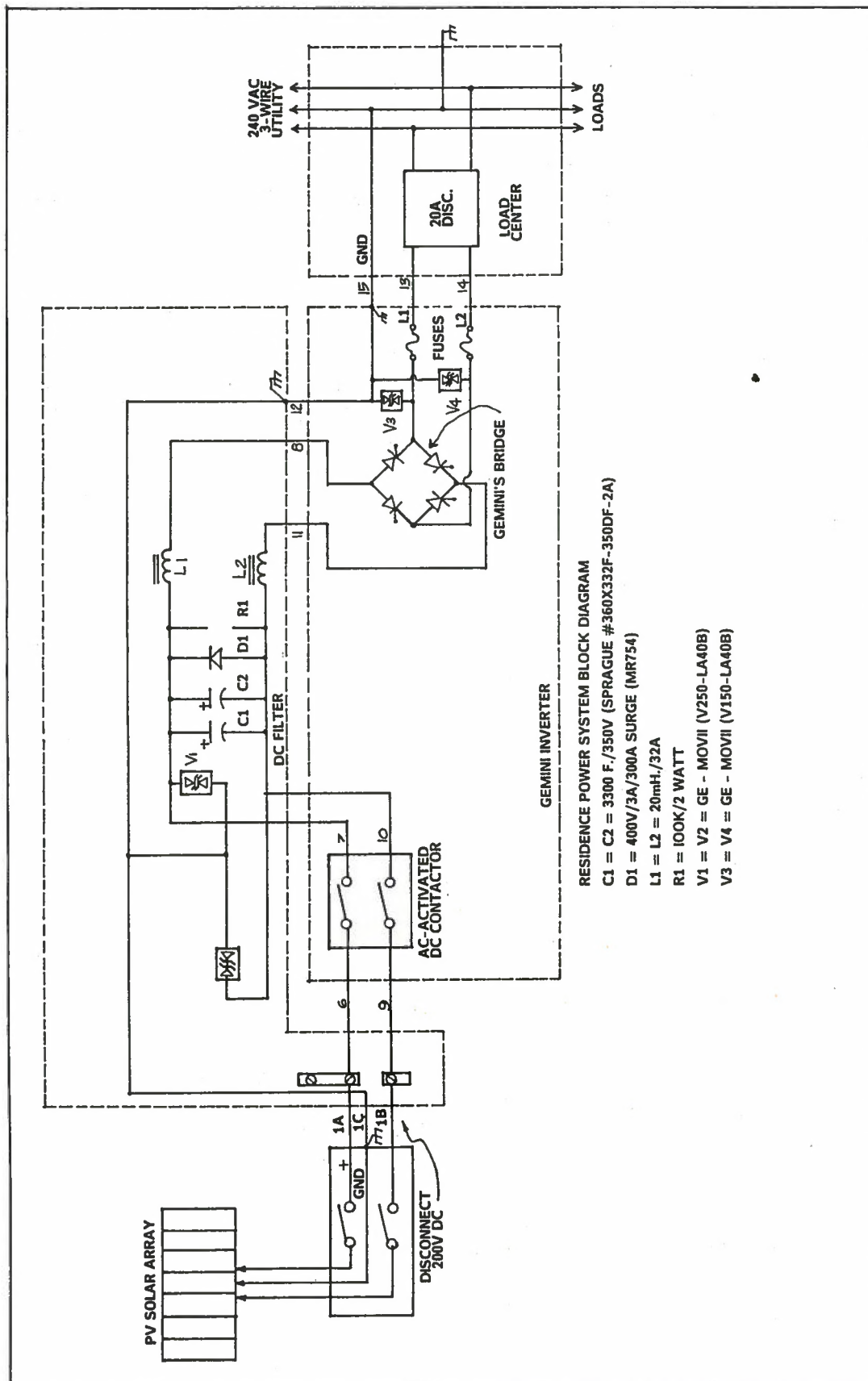


Figure 2. Photovoltaic System Schematic

## SECTION II

### TECHNICAL

#### A. RATIONALE FOR SITE SELECTION

Tyndall AFB was selected as the test installation for this effort because: (1) its relatively high daily insolation had been recorded for 2 years and, (2) HQ AFESC's Engineering and Services Laboratory is a tenant agency at Tyndall AFB.

A residence at 3140A Guardian Street was chosen as the construction site because of its approximate north-south orientation and because it is a one-half duplex where each single family residential unit is separately metered, enabling the adjoining unit (Quarters 3140B) to serve as a control element.

#### B. DESIGN

The PV array was a 2-kilowatt peak system that provides supplementary electricity for a military family of four persons residing in Quarters 3140A. The PV array contained 70 modules, each with peak power of 37 watts. The array was wired to produce at 28°C, a maximum power point (2,346 kilowatt peak) at 208 volts, 11.5 amperes. (The system wiring schematic is illustrated in Figure 2.)

The power-conditioning system included a 4-kilowatt Gemini inverter (Figures 3 and 4) and a balanced direct current input filter (Figure 5) designed by TriSolar Corp. These, along with both direct and alternating current disconnects and fuses, are housed in a weatherproof equipment enclosure on the east side of the house (Figure 6).



Figure 3. Direct Current Interface and Gemini Inverter Installed

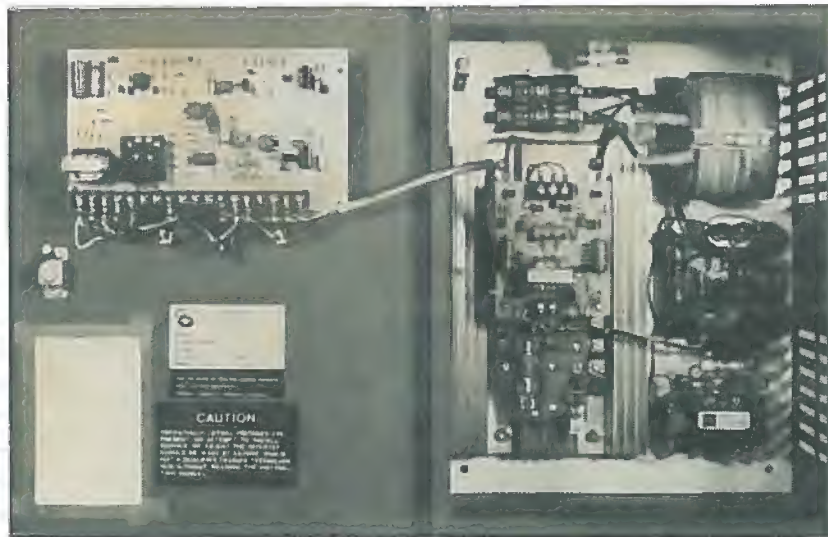


Figure 4. Interior View of Gemini Inverter

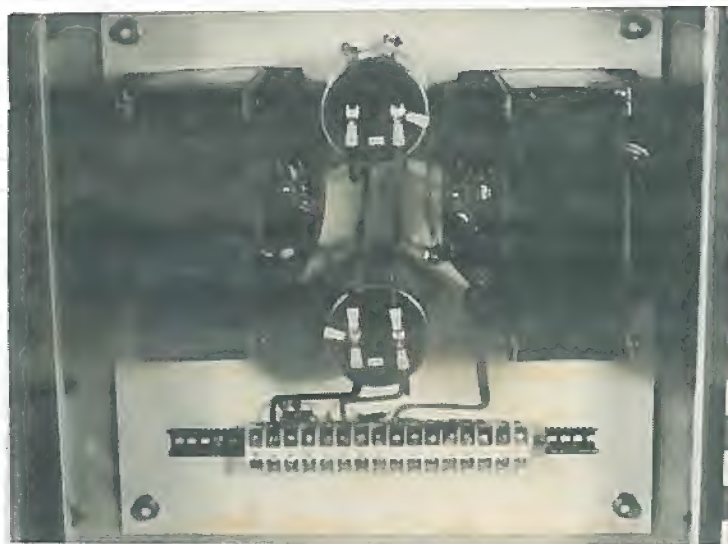


Figure 5. Interior View of Direct Current Interface

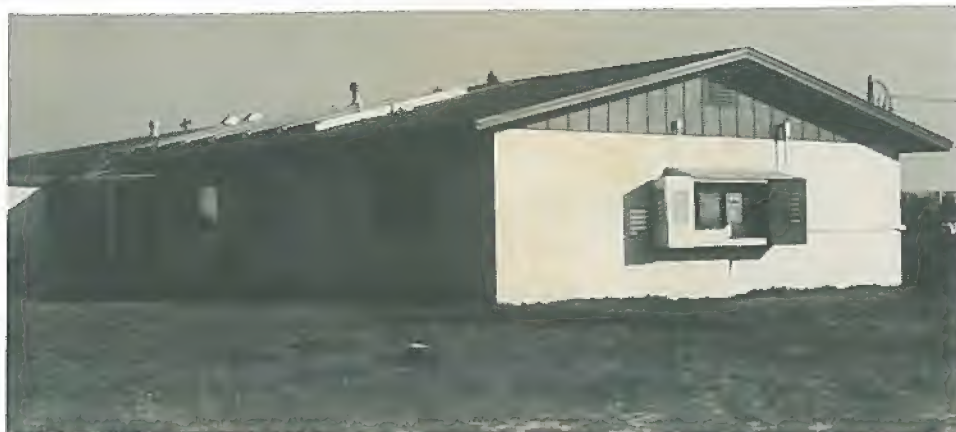


Figure 6. Tyndall Residence Equipment Enclosure



The lightning protection system included varistors for near-strike lightning protection, along with lightning rods and an extensive grounding system.

The modules feature glass-laminated construction (ARCO Solar ASI-16-2300) with cells laminated to form a weatherproof sandwich of tempered glass and coated metal. The modules have redundant output terminals, two per polarity, grouped at one end of each module; they are housed in a weatherproof plastic junction box with a removable screw cover. To prevent panel overheating from localized shadowing in high-voltage arrays, bypass diodes were installed on each module. The modules were arranged mechanically into seven strings of 10 modules and electrically grouped into 14 series groups of five parallel modules.

The array wiring used VNTC sunlight-resistant, flexible cable with Number 10 copper conductors (total loop resistance: 380 meters @ 28°C) to an array junction box mounted on the roof. Manual disconnection of array was accomplished with Bryant waterproof connectors. The array was connected to the power-conditioning unit by Number 10 VNTC conduit running through the attic and through the east side of the roof structure, down the side of the building into the weather protection structure. The wiring of the power-conditioning equipment and instrumentation, along with system wiring and conduit specification, is illustrated in Figure 2. The local power company provided grid metering features; the Air Force added electronic monitoring devices. The PV system utilizes a 4-kilowatt line-commutated Gemini inverter with a power factor above 65 percent at 2-kilowatt normal alternating current output and total harmonic (voltage) distortion below 15 percent. A plexiglass window was built into the equipment enclosure to observe the voltmeter operation.

The direct current interface unit, used with PV systems, allows common mode-free, virtually grounded, array operation without use of an isolation transformer. Inductors were sized at 20 megahertz each and located in each input leg of the array direct current (Figure 2 diagrams the interface with the Gemini inverter). Figure 7 shows the power factor, while Figure 8 portrays the efficiency of the Gemini inverter connected with the direct current interface.

Three forms of lightning protection were included in this system:

1. TriSolar provided varistors on both direct current and alternating current inputs to the inverter for near-strike protection (Figure 9). These can withstand strikes of up to 1000 amperes of induced current for 100-1000 microseconds---a "typical" near-strike.

2. Frame grounding at the ground bus in the residence load center was provided to absorb small direct strikes to the frame and reduce the induced load of indirect strikes.

3. Three air terminals were installed to the east, at the center, and west of the array along the roof-peak edge. Terminals were separately wired to earth ground to avoid damage from induced transients caused by currents in this ground wire (Figure 10). No air terminals were located south of the array to avoid shadowing.

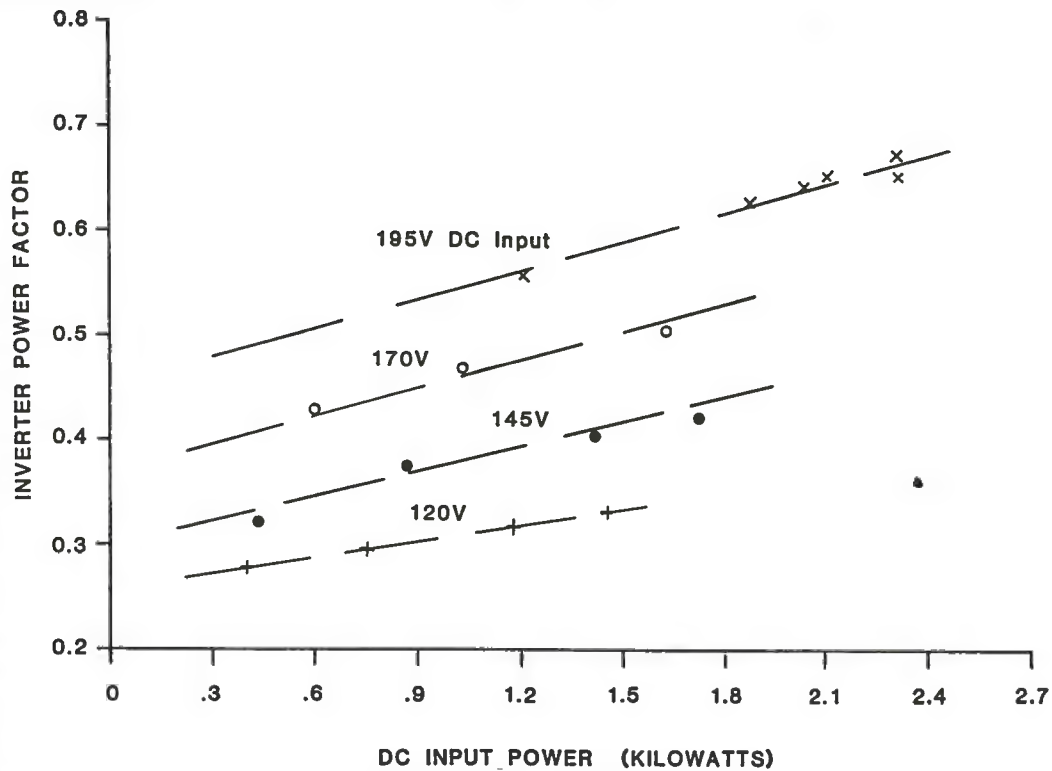


Figure 7. 4-Kilowatt Gemini Inverter Power Factor with 20-Megahertz Inductors

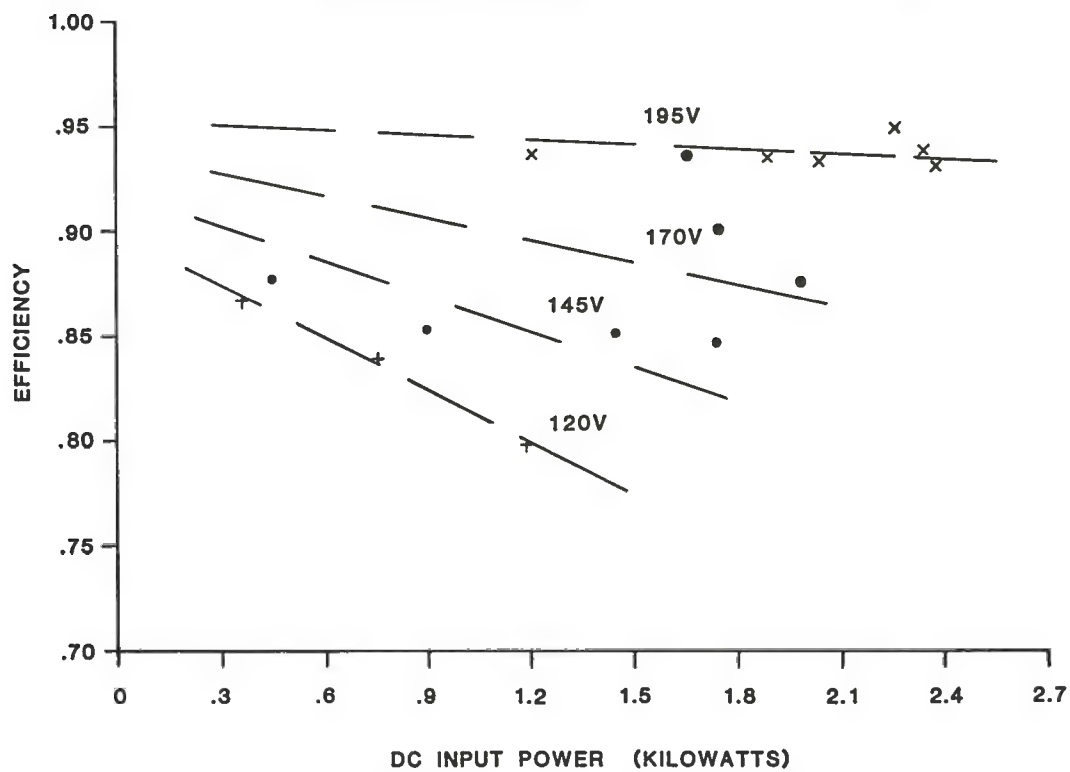


Figure 8. 4-Kilowatt Gemini Inverter Efficiency with 20-Megahertz Inductors

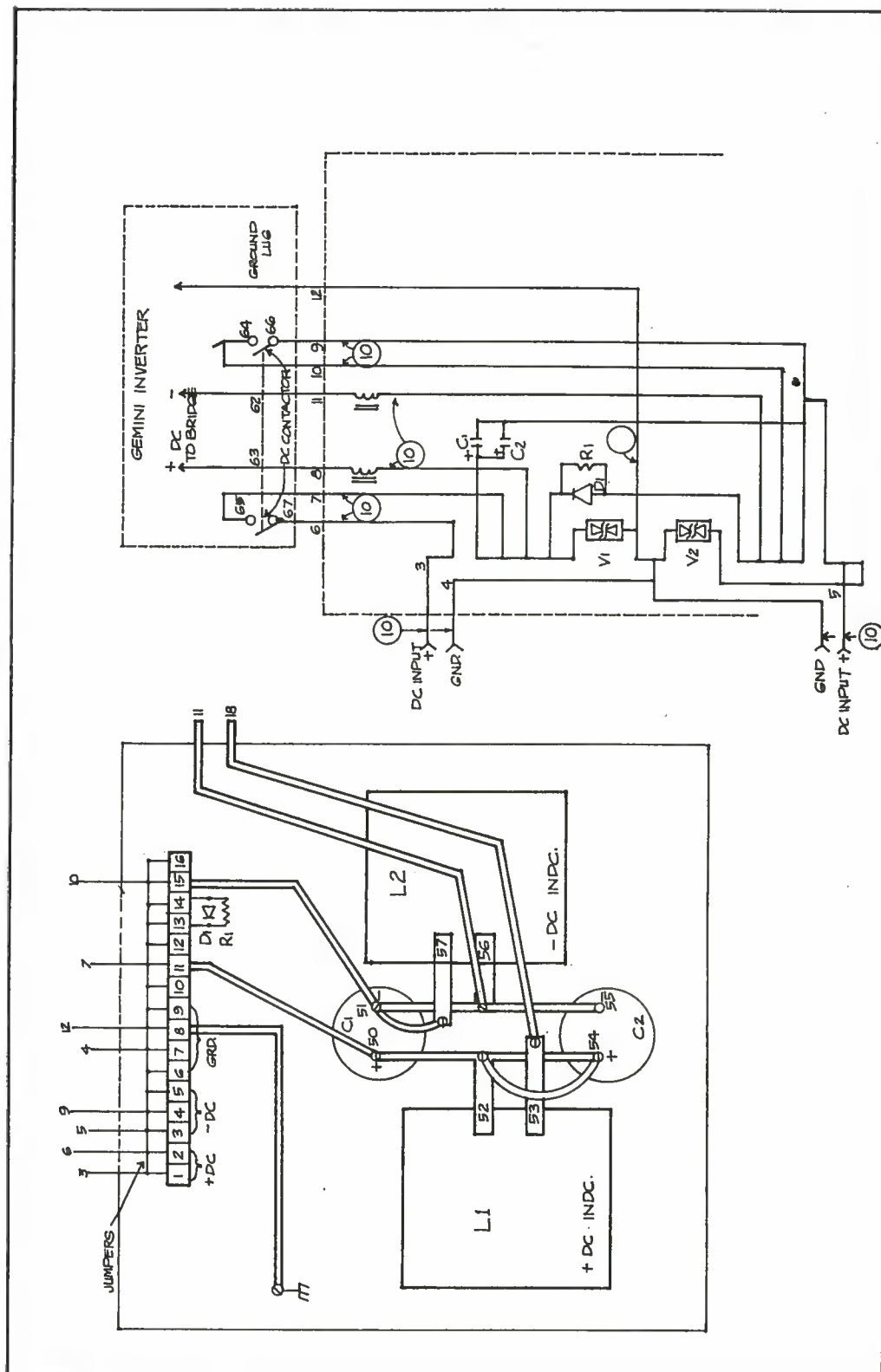


Figure 9. Grid Synchronization Protection.



Figure 10. View of Lightning Rods on Residence

The metering system includes three kilowatt-hour meters, one kilovoltampere meter, and a digital insolameter. One kilowatt meter measures the solar power contribution; another measures the net energy to and from the Gulf Power Company; the third meter measures the amount of power consumed by the household. The kilovoltampere reactive meter measures reactive power from the inductive load phase shift. In this meter, the voltage coil is shifted by  $90^\circ$  from its true value, and the product of this shifted voltage and the current drawn by the load represents the reactive power. These meters are electrically recorded by the local power company. The digital insolameter instantaneously measures the total horizontal insolation and accumulates the insolation data for the period chosen by the user. Figure 11 shows the electrical wiring diagram with meter connections.

The power-conditioning equipment enclosure is pictured in Figure 6. From left to right, the boxes inside the equipment enclosure are the direct current disconnect, direct current interface, Gemini inverter, and the output kilowatt-hour meters. Interior views of the interface box and inverter are shown in Figures 3 and 4, respectively.

Controls consist of a direct current disconnect switch, an alternating current disconnect switch, and a direct current interface box.

The direct current disconnect switch has one control handle on the front of the cabinet. This switch electrically disconnects the array from the rest of the system.

The alternating current disconnect is located exterior to the control equipment enclosure. This manually fused disconnect was locked in the "on" position to prevent tampering. The switch manually disconnects the solar power system without interrupting service to the quarters. The direct current interface box has no controls on its front. This box has live terminals inside, even when the inverter is turned off.





### C. DATA ANALYSIS

#### Definition of Terms:

V	=	Array direct current volts
I	=	Array direct current amperes
W/m <sup>2</sup>	=	Insolation in watts per square meter
PA	=	Array power in kilowatts at 185 volts and 1 kilowatt per square meter
Wh/m <sup>2</sup>	=	Integrated insolation in watt-hours per square meter over same time period
kWh	=	Integrated alternating current output power in kilowatt hours over same time period
PI	=	Inverter output power in kilowatts at 185 volts direct current and 1 kilowatt per square meter
NI	=	Inverter efficiency (calculated) at 185 volts direct current and 1 kilowatt per square meter
EDC	=	Direct current energy delivered by array per day
EAC	=	Alternating current energy delivered by inverter per day
NIA	=	Inverter average daily efficiency
kW/m <sup>2</sup> D	=	Daily insolation in kilowatts per square meter per day
IDC	=	Array current expected at 185 volts direct current

The purpose of this analysis was to establish, from measurements, the system's performance and efficiency conditions. Both the raw data and the individual calculated results for 12 months are shown in Table 1. The calculated data in Table 1 were converted to 14-degree global to relate to the 14 degrees of the house roof construction. All known algorithms to perform this conversion require that the solar data provide both the direct normal component and the diffused component. The only data available are the daily totals and do not include either component.

To provide a realistic estimate of the monthly 14-degree global insolation and predicted system performance (shown in Table 1), a manual calculation was performed:

$$SE_{14} = \frac{R_{15,M}}{R_{0,M}} \sum_{i=0}^n X_i$$

where:  $SE_{14}$  is total monthly insolation on 14° tilt, kWh/m<sup>2</sup>

$X_i$  is insolation for  $i$ th day (kWh/m<sup>2</sup>)

$n$  is number of valid days in the months data base

$R_{15,m}$  is 22-year total insolation on a south facing  $15^\circ$ -plane at Appalachicola, FL, for the  $m$ th month (Reference 1)

$R_{0,m}$  is 22-year average total insolation on a horizontal plane at Appalachicola, FL, for the  $m$ th month (Reference 1)

Also, the predicted, calculated array output, instantaneous insolation, array direct current volts, and array direct current amperes for each month were tabulated. The calculated array output power under standard insolation of 1 kilowatt per square meter, in kilowatts, is given by:

$$PA = \frac{V \times I}{(W/m^2)} \times 1 \text{ kW/m}^2 = \text{kilowatts}$$

This is plotted in Figure 12 and was also used in the formula for IDC:

$$IDC = \frac{(2.05 \text{ kW}) \times (\text{Insolation})}{(185V) \times (1 \text{ kW/m}^2)}$$

This is used to recalculate the corrected direct current-output currents in Figure 13 for 185 volts direct current. The predicted monthly average array was 1 kilowatt per square meter. The 2.05 kilowatt was an average power out of the array. The difference is probably due to the variation of array temperature from predicted, or the effect of not operating at the exact maximum-power voltage, or a combination of the two (since temperature affects the maximum power-point voltage).

The instantaneous inverter-output power is not measured directly. Before calculating the inverter operating efficiency under standard conditions, the inverter-output power under standard conditions must be calculated. This is done by using the integrated output power and the integrated insolation, as follows:

$$PI = \frac{(kWh) \times (1 \text{ kW/m}^2)}{(Wh/m^2)}$$

This permits the construction of energy formulas which make predictions based on the daily insolation (kilowatt per square meter per day): the direct current energy delivered to the inverter EDC in kilowatt-hours; the net alternating-current energy delivered by the inverter EAC in kilowatt-hours; and the average daily efficiency of the inverter, NIA, as given below:

$$\begin{aligned} EDC &= (2.05 \text{ kW}) \times (kW/m^2 D) \\ EAC &= 0.963 \text{ EDC} - 0.648 \\ NIA &= EDC/EAC \end{aligned}$$

To establish the inverter operating efficiency, the inverter-output power in Figure 13 was calculated using power values shown in Table 1.

The inverter power capacity is 4 kilowatts. Most of the 24-hour day is spent at zero-power level, and the sunny period is still well below the 4-kilowatt rating of the inverter. To determine true efficiency, the tare loss, or no-load loss, of the inverter is essentially a constant

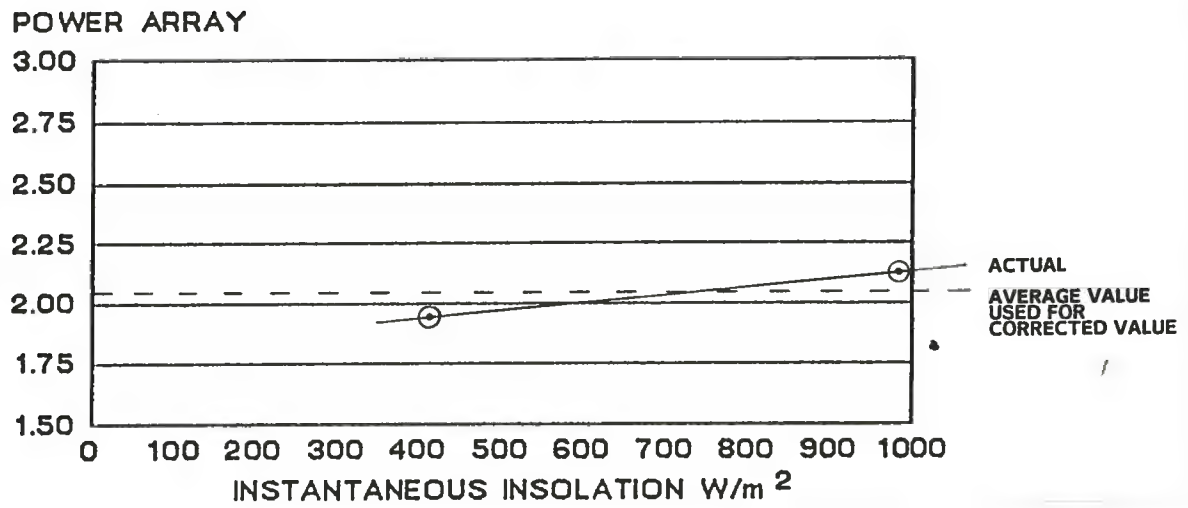


Figure 12. Corrected Array Power

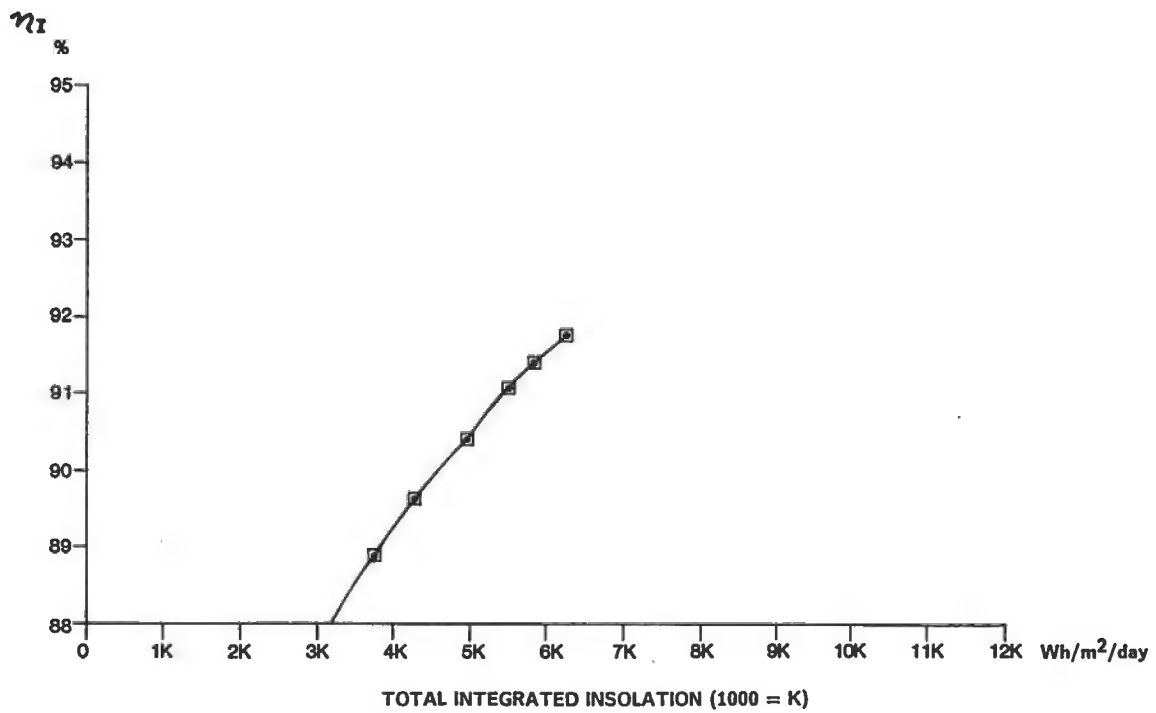


Figure 13. Average Daily Inverter Efficiency

TABLE I. PREDICTED AND ACTUAL PV PERFORMANCE SUMMARY  
MAR 84 - FEB 85

Predicted Performance Summary													
Aver Ambient Temp °C	MAR 11	APR 12	MAY 15	JUN 20	JUL 23	AUG 26	SEP 27	OCT 27	NOV 25	DEC 21	JAN 15	FEB 12	YEAR
Insolation kWh/m <sup>2</sup> /d (1)	3.58	4.33	5.11	6.03	6.33	6.22	5.94	5.89	5.28	5.17	3.94	3.24	
C <sub>T</sub> (2)	1.042	1.037	1.023	1.000	.986	.972	.967	.967	.977	.995	1.023	1.037	
Array Output kWh/day (3)	8.52	10.25	12.06	13.78	14.26	13.81	13.12	13.01	11.79	11.76	9.21	7.70	
Inverter Output kWh/day	8.09	9.74	11.46	13.09	13.55	13.12	12.46	12.36	11.70	11.17	8.75	7.31	
Inverter Output Corrected for Tare Loss kWh/day	7.55	9.22	10.96	12.62	13.08	12.65	11.98	11.88	10.70	10.67	8.22	6.77	
Actual Performance Summary													
House Load kWh	607	715	1510	2107	2510	2560	1575	920	1015	135	155	129	
PV System Output kWh	335	357	386	383	366	340	273	256	235	75	90	82	3175
Solar Incident on PV Array kWh	4794	4674	4822	4790	4680	4210	4255	4033	2971	2620	2885	3152	
Inverter Eff %	81.7	76.5	92.7	92.5	90.1	92.3	84.	86.9	88.6	98.6	89.6	81.7	
Array Conversion Eff of PV Sys %	6.4	6.8	6.0	5.8	5.5	5.5	5.6	4.9	4.9	4.1	4.5	5.1	
Days in Data Base	31	27	30	30	31	29	27/31	25/30	29	10/31	12/31	10/28	
System Cost Savings	17.49	18.60	20.11	19.95	19.07	17.71	14.22	13.34	12.24	3.91	4.69	4.27	165.42

- (1) Based on Apalachicola, FL, azimuth 30° from south, elevation 14° roof angle  
 (2) Based on 0.45%/°C  
 (3) Inverter Efficiency 0.95% (Gemini)

loss under all conditions, while the rest of the losses are approximately proportional to power level. The tare loss had been measured in the laboratory at 27 watts. This gives a daily tare loss of  $27 \text{ watts} \times 24 \text{ hours} = 648 \text{ watt-hours}$  per day.

### SECTION III

#### SYSTEM PERFORMANCE

##### A. ACCEPTANCE TESTING

The PV system at Tyndall AFB was accepted after the contractor completed installation and demonstrated that the system functioned according to system specifications. The general contractor submitted all operation, maintenance, and repair documentation before acceptance. Formal acceptance occurred in November 1983; however, the system had been operational since June 1982.

Meters kept records of the total power consumed by the Tyndall house, power delivered by the PV system, and power delivered by the utility grid. Table 1 includes the data on actual power delivered by the PV array compared with predicted values. Approximately 23 percent of the facility's 13,938 kilowatt hour annual energy requirement was provided by the PV system.

The wide variance between the predicted and actual data recorded in Table 1 is due partially to downtime caused by surge suppressors in the inverter. The inverter's grid synchronization circuit received several lightning strikes that destroyed the surge suppressor.

The general operating parameters at the time of acceptance were:

- o 211 volts direct current from array;
- o 240 volts alternating current from power company;
- o 450 watts per square meter insolation;
- o 208 volts alternating current inverter voltage;
- o 5 amperes inverter amperage; and
- o Synchronization with electric utility grid.

A logsheet was developed to permit AFESC and the house occupants to record data and calculate energy for the PV array (Appendix A contains a sample logsheet). Voltage and current readings were taken to ensure that the system was operational. The three power meters were replaced five times during the year.

The logsheet was also used to record downtime and information about each failure's cause. Weather data, including wind direction and velocity, and temperature and solar insolation level were recorded for use during the subsequent system performance analyses. All PV system maintenance repairs were performed by AFESC/RDCS.

For example, Florida lightning storms destroyed the grid synchronizing transformer suppressors several times. However, repair cost was considered minimal at 12 labor hours plus \$65 for material cost.

The capacity factor for a power system is based on the amount of energy the system can produce in 24 hours if run at its peak. The energy production level for earthbound power systems is generally much less than for other types of power plants.

The Tyndall house PV is rated at 2-kilowatt peak. The monthly base level is 48 kilowatt-hours per 24 hours, times the number of days in the month. Table 1 shows a relatively consistent factor of 20 percent, which is typical of PV systems. During the months of December, January, and February the house was not occupied fully each month. An outline of system savings can be found in Table 1.

If all conditions remained the same, and if the house were continuously occupied each year, it would take 407 years to pay back the original \$77,000 cost of the PV system.

## **B. PERFORMANCE SUMMARY**

The PV system operated in paralleled synchronization with a local alternating current power grid. It was only out of operation at low sunlight, when the alternating current grid was inoperative, or for system repair. The system can be isolated from the alternating current grid by power disconnects.



## SECTION IV

### CONCLUSION AND RECOMMENDATIONS

The Tyndall house PV electrical power system was adequately designed and satisfactorily provided 2-kilowatt capacity energy as required by the house occupants. The objectives of this project were met by:

- o Demonstrating the performance of a 2-kilowatt grid synchronized PV system.
- o Providing the Air Force experience with terrestrial PV power technology.

While the economic feasibility of a PV system was never in question, it was found that it is not cost-effective to use such a system where an electrical grid system already exists. However, situations exist in which PV arrays could be cost-effective; consequently, each application must be studied independently. Table 2 was developed to permit a comparison of the pay-back breakpoint using the local power company rates and distribution construction cost. According to these data, a \$77,000 PV system could be justified for daytime use only if it were located at a distance greater than 7.6 miles from an existing power system and when electric utility cost exceeds 0.05 cent per kilowatt hour.

If energy costs increase and PV system costs decrease, future PV systems may serve as cost-effective, alternate sources of electrical power.

A complete understanding of the economic feasibility of future military PV projects requires a detailed life-cycle economic analysis. This analysis should consider all system capital and O&M costs, the discount rate, the current price of electricity at the site, the limited electrical production time of a PV system, and an assumed escalation rate for the future electrical cost rate.

TABLE 2. COMPARISON OF COST AND PAYBACK

Distribution Line Installation Cost								
(Miles) Cost (Dollars)	2 20K	4 40K	6 60K	8 80K	10 100K	15 150K		
Grid Power Cost								
Cost kWh 4380 kWh/yr(\$)	.05 219	.08 350	.10 438	.12 526	.15 657	.20 876	.25 1095	.30 1314
PV System Construction Cost								
Cost Per Peak Watt 2 kW cost(\$)	\$30 60K	\$25 50K	\$20 40K	\$15 30K	\$10 20K	\$5 10K	\$2 4K	\$1 2K
Annual System Cost								
Electricity Rate/Mile	.05	.08	.10	.12	.15	.20	.25	.30
2Mi	20219	20350	20438	20526	20657	20876	21095	21314
4Mi	40219	40350	40438	40526	40657	40876	41095	41314
6Mi	60219	60350	60438	60526	60657	60876	61095	61314
8Mi	80219	80350	80438	80526	80657	80876	81095	81314

## REFERENCE

1. Publication FSEC-77-3, "Mean Solar Radiation for Florida Cities," Florida Solar Energy Center, April 1977

APPENDIX A  
SAMPLE LOG SHEET

DAILY MEASUREMENTS  
(TYNDALL AFB)

DATE \_\_\_\_\_  
TIME \_\_\_\_\_  
INSTANTANEOUS INSOLATION \_\_\_\_\_  
TOTAL INTEGRATED INSOLATION \_\_\_\_\_ \*RESET\*  
DC INPUT VOLTAGE \_\_\_\_\_ VOLTS  
DC INPUT CURRENT \_\_\_\_\_ AMPS.  
KILOWATT HOUR READING \_\_\_\_\_ kWh

DATE \_\_\_\_\_  
TIME \_\_\_\_\_  
INSTANTANEOUS INSOLATION \_\_\_\_\_  
TOTAL INTEGRATED INSOLATION \_\_\_\_\_ \*RESET\*  
DC INPUT VOLTAGE \_\_\_\_\_ VOLTS  
DC INPUT CURRENT \_\_\_\_\_ AMPS.  
KILOWATT HOUR READING \_\_\_\_\_ kWh

DATE \_\_\_\_\_  
TIME \_\_\_\_\_  
INSTANTANEOUS INSOLATION \_\_\_\_\_  
TOTAL INGRATED INSOLATION \_\_\_\_\_ \*RESET\*  
DC INPUT VOLTAGE \_\_\_\_\_ VOLTS  
DC INPUT CURRENT \_\_\_\_\_ AMPS.  
KILOWATT HOUR READING \_\_\_\_\_ kWh

DATE \_\_\_\_\_  
TIME \_\_\_\_\_  
INSTANTANEOUS INSOLATION \_\_\_\_\_  
TOTAL INTEGRATED INSOLATION \_\_\_\_\_ \*RESET\*  
DC INPUT VOLTAGE \_\_\_\_\_ VOLTS  
DC INPUT CURRENT \_\_\_\_\_ AMPS.  
KILOWATT HOUR READING \_\_\_\_\_ kWh

\*\*\*Measurements should be made at the same time every day.  
Best time to take measurements is between 10:00 a.m. and  
2:00 p.m.